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Schematic Categorization and Definition of Applied and Target-oriented Digital Twins

Schematische Kategorisierung und Definition Angewandter und Zielgerichteter Digitaler Zwillinge

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Abstract: Digital Twins are of high interest in a variety of research fields as well as industry sectors because they enable, among other things, more efficient maintenance and faster product development and production planning. However, current definitions of Digital Twins in the literature are often varying, contradictory, or non-comprehensive from a practitioner's perspective. Therefore, no universally accepted standardized definition for the development of Digital Twins exists. Thus, we propose a shift in the current scientific discussion towards economic and target-oriented concepts. Our main thesis is that there exists no ubiquitous Digital Twin but specialized concepts for different industry sectors, stakeholders, and applications. We discuss this idea further in the context of the automotive industry. We propose a framework to differentiate versions of a Digital Twin expressed by a morphological matrix in order to make a distinction from pure simulation models. In future work, the usefulness of this framework should be tested and applied for more industry sectors.

1 Introduction

The idea of a Digital Twin (DT), described as a virtual representation of a physical system but also a functional entity on its own, was first defined in 2002 by Grieves. This representation should include all obtainable information of the assets of the real physical system (Grieves and Vickers, 2017). Thus, the DT acts like a physical twin of a system in a virtual set-up. Tao et al. (2019) describe the first few years of research in the field of DTs as a formation stage, until in 2011 the number of publications about the topic started to continually increase. Since 2014, Tao et al. (2019) measured a rapid growth phase of DT research starting with a first white paper by Grieves.

In the literature, Kritzinger et al. (2018) describe 55 % of conducted research about DTs as concepts, while 26 % of papers are described as case studies. However, Kritzinger et al. (2018) differentiate between research about full DTs, using a bi-directional automated data flow, and Digital Models (DM) with only a manual data flow and Digital Shadows (DS) with only an automated data flow towards the digital representation. Thus, a minority of concepts and use cases discuss (from the authors' perspective) true DTs. In addition, Kuehner et al. (2021) show that most reviews do not provide an explicit definition of DTs and thus, they identify a lack of focus in the terminology of DTs with little progress in the development of a common definition over time. This is highlighted by, e.g., Negri et al. (2017) naming 16 different definitions of a DT. This indicates that there exists a problem with the current methodology in defining a DT and the field of research stagnates in this aspect.

Kritzinger et al. (2018) identify multiple different areas of application of DTs. Biesinger and Weyrich (2019), which focus on the automotive industry, also find different applications and, in addition, benefits of an applied DT in the current body of literature and use cases. Overall, the benefits and applications in the literature are neither mutually exclusively defined nor completely exhaustive but exist in all areas of the business activities of the automotive industry. While the potential business impact in the automotive industry is assumed to be high, Kober et al. (2022) state correctly that the value added by DTs is commonly unclear and intangible. Newrzella et al. (2022) propose a first concept to evaluate use cases and benefits of DTs but do not discuss their relation to the definition of DTs.

This indicates problems in the research field of DTs: definitions are unclear, varying, contradictory, or non-comprehensive, the benefits for companies are only vaguely understood, and the application areas not comprehensively defined. From this follows that no accepted standardized definition for DTs exists. This paper contributes to this discussion first, by a clarification why no standardized concept can exit, since stakeholders, applications, purpose, and industries vary; and second, by making a proposal on how to discuss DTs more targeted. We discuss the literature and the contradicting aspects of the definitions along a developed taxonomy in Section 2. Subsequently, we add important challenges from a practitioner's perspective of a current DT implementation project in the automotive industry in Section 3, which completes and contextualizes the perspective from the literature. As a methodology for a target-oriented DT conceptualization, we propose in Section 4 a framework to discuss the DT concept in future publications or industry projects more focused using a morphological analysis. Using the framework in Section 4, we show in Section 5 an application at a project in the automotive industry to improve the steering of a DT project initiative. An outlook and conclusion are given in Section 6.

2 Literature Review and Set-up of a Taxonomy

A taxonomy is helpful to structure DT concepts in a meaningful way. Thus, we define four categories of aspects of DTs commonly discussed in the body of literature.

The first category is the task of a DT. One frequently mentioned aspect in definitions, use cases, and concepts is the simulation task of DTs. Simulations are often imitations of the physical processes of an asset in order to gain information about future problems occurring in the physical asset. Revetria et al. (2019) state that the common understanding is that DTs are representations reflecting the physical asset. Kritzinger et al. (2018) would otherwise describe the use of DTs as simulation models as DMs since the data flow is not automated in both directions. Borth et al. (2019) explicitly discuss the bi-directional automated data flow and they connect it with a use case by addressing the control aspects of a DT. Using control and simulation aspects instead of data flow adds benefits to the discussion of DTs: we shift from a technical discussion to a use case discussion. This enables a better understanding of the value and business impacts by DTs. Besides simulation and control, other authors, e.g., Tao et al. (2018), add intelligent optimization as tasks of a DT. Another aspect in the literature is the maintenance or monitoring usage of DTs. Zhuang et al. (2018) describe the DT also as a solution for data management.

The second category is the depth of a DT. This is the precision of the used underlying model and scope of the data flow. Authors such as Brosinsky et al. (2018) define DTs as software-based abstractions of the underlying complex physical systems. The model is not a true copy of the real system but reflects the points of interest of the analysed systems. Other authors such as Glaessgen and Stargel (2012) define the DT as “ultra-realistic”. This is a huge difference to the model-based abstractions and requires much more complex implementations, sensors, and interfaces between DTs and the physical world. The depth is essentially the degree of realism of the DT.

The third category is the width of a DT. In modern production, each system can be disassembled into different interacting subsystems. Different authors state a different number of subsystems necessary to set up a DT. Grieves and Vickers (2017) are describing the DT as exhaustive and using all obtainable information of the assets. Other authors such as Glaessgen and Stargel (2012) define DTs as specialized, only focusing on important parts of the overall system.

Authors focusing on aeronautical applications often define DTs with a high depth but small width. On the other hand, authors from manufacturing often focus more on abstract simulations, which cover the whole production system equally and thus, define DTs with a small depth but high width. This indicates an industry-specific need for definitions. The industry sector might be relevant for a useful DT taxonomy.

The fourth category is the dependency. A common opinion is that a DT strictly follows the physical asset and is a representation of an original object. This is highlighted by Zobel-Roos et al. (2019) defining DTs as copies or by Haag and Anderl (2018) stating that DTs are developed alongside physical models. Kuhn (2017) describes a different approach and states that DTs can exist independently or without physical counterparts.

Besides these technical requirements, the organizational complexity, relevant stakeholders of the DT, and different areas of application also shape the definitions and concepts of DTs. These requirements are from a higher-level perspective since they dictate the purpose and application of the DT but not the technical definition.

3 Challenges from a Practical Application

In this section, we share our lessons, occurring challenges, and problems of the current implementation project of DTs at the Mercedes-Benz Group AG. The focus is on the pain points which occurred during the project. A brief overview is given as follows.

The first pain point is the lack of a standardized definition, which is a phenomenon in the literature as well as in practice. This results in an extensive amount of necessary communication to align ideas, proposals, concepts, and visions for DTs. Furthermore, each new project member needs a specific briefing since each individual definition of a DT highly differs based on experiences and knowledge from former projects.

The next pain point is accelerated due to the large width often associated with DTs. Due to different applications, systems, and areas of applications, experts from product development, maintenance, operations, production planning, and management functions need to align on a common approach and methodology. This kind of interaction is hindered by a different amount of technical knowledge, perspectives, visions, or different approaches and methodologies in different industry fields. Larger project set-ups also lead to staffing shortages.

In addition, current models are often not sufficient for a transfer into a DT. There exist, e.g., no up-to-date kinematic simulation models in operations since simulations are only conducted during planning. After the commissioning, the simulations do not have a back-loop nor updates of the real physical assets. In one example, a model of a lift for a car body lacks the necessary kinematics since the supplier does not validate the lift's behaviour in the planning simulations. Up to now, no resources are assigned to these tasks since no economic reasons exist to develop a full kinematic model of all assets. Furthermore, the required time, process and technical knowledge, and the required materials or software to set up a DT with a high width and depth are extensive and business cases are often opaque. The cost of a DT highly depends on the planned depth and width and a DT project initiative might stress the budgeting of a company.

The final pain point is a tendency to create over ambitious DTs with higher depth and width than necessary. Often, the objectives, and thus, the complexity, are raised in the hope that a future DT will cover every system and aspect of the use case, which then increases budgets and lowers the profitability of the DT. We associate this with the psychological phenomenon in consumer behaviour of the Diderot-Effect proposed by McCracken (1988). Simplified, consumers have a need for completeness and uniformity in a gathered collection. Here, the DT needs to be complete and cover all systems and contingencies. Degnegaard (2010) describes this effect in change management when the scope of projects is continuously increased.

In summary, five challenges occur in a DT development due to an unclear definition:

- Increased communication and alignment efforts in order to define the scope.
- Organizational complexity to align different experts and stakeholders of the DT projects. Thus, also a shortage of staffing can occur.
- Precise data models do not exist and there is only a limited economic incentive to develop models with the necessary depth for DT applications.
- The business case of a DT is opaque which hinders efficient budgeting.
- The Diderot-Effect results in an overambitious scope of DTs.

4 Proposed Morphological Analysis Framework

There are limitations and requirements to separate DTs from digital tools and models:

- A DT must at least have an automated uni-directed interface, either towards the physical or digital representation. A separation of a DS and DT is later discussed, but the proposed framework covers both (Kritzinger et al., 2018).
- A DT differs from a model, simulation, or process mining analysis since its lifecycle exceeds that of a simulation or model. The DT rather covers the whole lifecycle of the (physical) components (Talkhestani et al., 2018).
- A DT acts as a universal interface within the enterprise software landscape and is capable of aggregating data from all sources (Ströer et al., 2018).

The objective of the framework is to include all possible and in literature contradictory definitions to enable a target-oriented DT categorization for a streamlined definition in an application. The given definitions and categories should be mutually exclusive but collectively exhaustive as far as actionable. Therefore, we sometimes combine aspects with a high degree of overlap which the literature often mentions separately.

Within the proposed framework, we differentiate the strategic layer, which covers the industry sector, the organizational set-up, i.e., the target user for the DT, the purpose, i.e., the area of application of the DT, and the business case.

Level (1) of the framework's differentiation is the industry sector. We propose to use the ISIC Revision 4 definition of industry sectors, excluding Section T: activities of household as employers, due to lack of DT relevance, and Section U: extraterritorial organizations, since they are included in Section O: public administration for the purpose of DTs. The defined industry sectors differ significantly regrading requirements, challenges, DT use cases, and economic application. Thus, we assume DT solutions will differ significantly within these industry sectors.

Level (2) covers the internal stakeholders. Stakeholders are the beneficiaries of a DT, which might differ from the users or developers. The here presented stakeholders are related to a functional organization structure but lack the ability to holistically cover all possible set-ups since a wide variety of organizational structures are implemented and differ between industry sectors. Thus, the stakeholders are always customized within the applied company and industry sector. The framework is adjusted for each organization for which it is enrolled but should always reflect the full organizational structure of the company. However, a DT benefits a certain function, defined in the next level in more detail, and thus, respective stakeholders will arise for organizations with a divisional structure or matrix structure within a division or matrix nods.

As level (3), the area of DT application is defined. We propose for this a macroscopic view of the value creation of an organization founded on the considerations of the resource-based view initially proposed by Penrose (1959). An organization receives inputs and converts these within its own environment into outputs, which are then distributed. Outputs are the products and services offered by the company. Inputs are all resources necessary for production. The transformation process from inputs into outputs is the production. The spatial and temporal provision of goods and the material flow within the production is the distribution of outputs and inputs. The facility covers the business environment. All tasks are organized by an administration. The wording changes within the service industry but the logic stays unchanged. These areas are the resources of an organization. The DT is a company-specific capability of the organization to improve productivity, which then leads to a competitive advantage, based on the definition by Amit and Schoemaker (1993). Further discussion is necessary if distribution must be split up into the logistics suppling resources, the material flow within the facility, and the sales distribution of products and services.

Level (4) covers the definition of the business case, which acts as a guideline for a later operational implementation. This business case specifies the economic optimization objective. Regardless of whether output is maximized given a fixed input or input minimized given a fixed output, the economic objectives are broadly defined either as a revenue increase or a profitability increase. Thus, a DT which optimizes revenue is increasing the number of units produced by an increase in production efficiency, is accelerating the business development by opening new markets, or is adding value to the product which enables price increases or reaches new customers. If the DT focuses on profit, a reduction in organizational complexity results in reduced fixed costs. A reduction of variable costs is also part of production efficiency. The business case must specify the targeted economic optimization aspect. This simplifies the applied benefits by Biesinger and Weyrich (2019) and creates comprehensive but mutually exclusive categories of business benefits. From an economic perspective, a DT offers particularly high value when the physical counterpart is not available.

The second layer is the operational layer describing the technical DT implementation. The task of the DT is the level (5) and defines the application of DTs. As found in the literature review, tasks are the data management, monitoring, simulation, control, or optimization of the systems which the DT represents. These tasks differ regarding their knowledge creation and data intelligence capabilities. We define predictions as the result of a simulation and system analysis as part of the monitoring. The tasks are not fully mutually exclusive since higher functionalities such as optimization require a data management or simulation capability. Thus, the task can be ordered by their dependency and intelligence capabilities. It is important that, e.g., data management is often not the objective of the DT development and therefore, it is not required to model and design the data management in more depth than necessary to fulfil the higher functions' requirements. Data management and monitoring only require a uni-directional interface, while control and optimization strictly require bi-directional interfaces. This separates the DT and DS along the definition by Kritzinger et al. (2018) and is aligned with the statement by Delbrügger and Rossmann (2019) that the common understanding of a DT is that it is more powerful than a DS, which primarily accumulates data. The defined tasks are compatible with most literature taxonomies, e.g., by Kuehner et al. (2021). The tasks of a DT are illustrated in Figure 1.

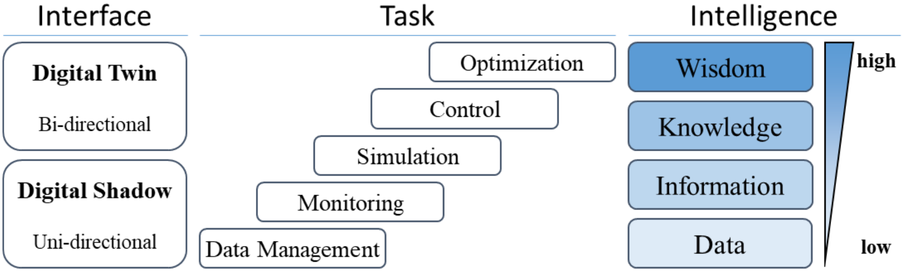

Figure 1: The tasks of a DT along increasingly complex applications of intelligence using the data, information, knowledge, and wisdom approach.

The depth is defined as level (6). This includes the precision of a representation of the physical assets in a virtual realization and the degree of analytical modelling of the physical world. A high depth is represented by "ultra-realistic" DTs as defined by Glaessgen and Stargel (2012). At a medium depth are model-based abstractions, while a low depth covers logical abstractions without physical models. Complementary at level (7), the width covers the scope of interfaces and (sub-)systems. A DT by Grieves and Vickers (2017) has a high width since it covers all the obtainable information, while Glaessgen and Stargel (2012) use a low width by specializing on certain subsystems. Depth and width are not categorical but continuous spectrums of DT implementations. This makes them less comparable, but the defined scope of the DT should give good indications of these dimensions. The complexity of an implementation scales over-proportionally by the linking between depth and width.

The last level (8) describes the dependency and which system, either the physical or the digital, is the leading system defining the as-is-state. It depends on whether the physical implementation is a representation of the digital set-up, or the digital representation is based on the physical set-up.

The upper management is involved in the strategic definition. The operational project management defines the DT using the strategic alignment. Thus, the operational layer is planned and executed to fulfill the requirements defined by the management in the strategic layer. A technical implementation is in this sense business case and purpose driven. Implementations are only from such width and depth as business cases and strategic objectives require. This approach enables a delimitation of the DT definition and should be applied prior to a use case evaluation as proposed by Newrzella et al. (2022) to ensure comparability of use cases and to define internal responsibilities of stakeholders. The proposed morphological matrix is given in Figure 2.

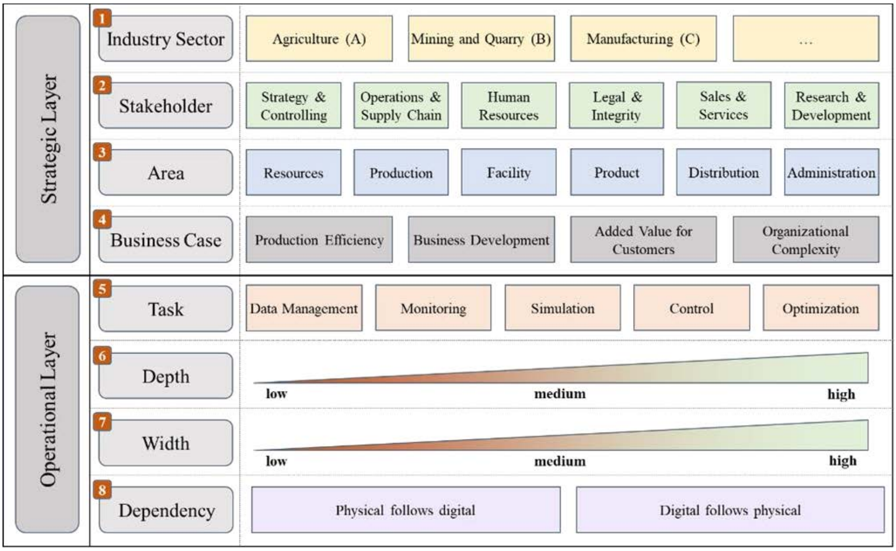

Figure 2: The morphological matrix of Digital Twins.

5 Exemplary Application of the Proposed Framework

The framework is applied to an implementation project at the Mercedes-Benz Group AG. First, the strategic layer is defined. The industry sector is given at level (1) of the morphological matrix as “Manufacturing”. While trivial in this case, the development of standard software or DT solutions for specific industry sectors might differ significantly so that the industries must be defined within a management decision.

The upper management is the owner of the DT project and is responsible to fill out the strategic layer of the morphological box. One project module of the DT initiative is in the “Operations” department, more precisely in production planning. This is the stakeholder of the corresponding project module covered by level (2). The production planning focuses on faster start-up times of a new product line. This scope includes the first production layouts based on the given drafts and prototype vehicles by product development as well as the fine-tuning, supplier selection and steering, and plant construction. The planned improvements are decreasing fix costs of production before the product launch. Thus, the area of application and level (3) of the morphological box is the “Production”. The business case is driven by a decrease of “Organizational Complexity”, which corresponds to level (4). This information is transferred from the management to an operative project leader. The management has defined the strategic objectives of the project and the operative project team must find solutions based on the given requirements by the management.

Next, the operational project team completes the operational layer and proposes a DT of cycle time planning. Until now, cycle times were planned in spreadsheets without interfaces to other systems. A DT of cycle time planning enables a prior planning, testing, and simulation of the proposed cycle time configurations before a physical implementation and thus the dependency, level (8), is “Physical follows digital”. The focus is on a simulation of the cycle time planning, and no data needs to be fed-back into subsequent systems. The objectives of the DT include the validation of alternative cycle time set-ups, benchmarking with the current cycle time configuration, and long-term simulation of cycle times. Thus, the task, level (5), is “Simulation”. Subsequent production or logistic processes are considered as given. New requirements are handed over to the person responsible for these processes. Thus, the width, level (6), is low. The production processes are broken down into subprocesses. Each subprocess has a cycle time imported from a cycle time library. A further break down as by the process library is not necessary. Technological process diagrams or kinematics do not need to be fully recorded. Thus, the depth, level (7), is medium.

Different DT definitions apply for each project, e.g., a development department might focus on added customer value of a product or maintenance might define a DT for the material flow to reduce organisational complexity. Within the same project, multiple different DTs might be developed, and the same stakeholders define multiple DTs for different business cases or application areas. Not all created DTs might be covered by current literature definitions but can be aligned using the proposed framework.

While it is trivial if analyzed ex post, the framework enables an efficient discussion of the objectives, a better common understanding, and accelerated communication and development. It solves following challenges of implementation projects:

- A clear scope of the project is applied. This enables a project monitoring, if the project is still within the defined scope and reduces the Diderot-Effect.
- The framework enables a brainstorming model to discuss concepts and ideas more focused. This optimizes the required amount of communication and alignment.
- A budgeting of the project is facilitated, and an economic business case is communicated and focused. This solves the opaque business case.
- The identification of stakeholders and experts is facilitated. In the given use case, cycle time experts must be involved but process developers or experts from production control are not required. The project team is downsized to the relevant experts. This then saves staffing capacities.
- The technical development tools are set up more efficiently since tools, interfaces, software suppliers, and data sources are defined faster. This is a targeted effort towards specific simulation models and tools with a clearly defined business case. An economic use for, e.g., kinematics, and budgets for these tasks can be justified.

6 Conclusion

This paper provides the research and practitioner community with a framework for defining and categorizing DTs and thus enables a broader view with economic usefulness in mind. We can demonstrate that this definition is helpful for practitioners. From an academic perspective, this shows that a DT is a broader concept consisting of different solutions where digital and physical assets and processes interact. The proposed broader DT concept reflects the wide variety of mutually contradictory definitions without excluding definitions. In addition, it is shown that each DT is different since each has different tasks, objectives, and set-ups. Thus, each DT needs different resources and competencies. Furthermore, this concept enables a novel project management method and structure for an individual development of DTs and a targeted knowledge management for DTs.

To our knowledge, this is the first introduction of a methodological framework for DT projects in practice using a morphological view, combining aspects from engineering, computer science, business economics, organization theory, and project management. We are currently planning a comprehensive validation of the proposed concept using expert interviews from a variety of industry sectors.

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